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ABSTRACT

A number of characteristics of accelerators relevant to their use as "meson factories" are discussed, and a comparison made of various types on the basis of these properties. In addition to the most popular types for this application--the isochronous cyclotron and the linear accelerator--the FM cyclotron, alternating gradient synchrotron, FFAG synchrotron, and electron accelerators are discussed briefly with respect to various attractive features concerning energy, intensity, duty factor, extraction, and cost.

COMPARISON OF ACCELERATOR TYPES†

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A. GENERAL REQUIREMENTS

Before examining the characteristics of specific machines which might qualify as "meson factories" (i. e., accelerators in the π-meson energy range providing substantially higher meson intensities than presently available), some of the general features which are desirable in such a device should be listed. These features must be treated with much more respect than for the last generation of meson producers, for the new machines will be in competition with the older ones. The institutions that are considering installations of this type are almost universally motivated by a desire to establish themselves in high-energy physics by making significant contributions in a field which has already been extensively, though by no means exhaustively, explored. High beam current in itself is not enough to insure success; factors influencing utilization, flexibility and simplicity of operation and maintenance must be carefully considered.

1. Energy

The total cross section for production of π mesons by protons rises from a threshold at about 200 MeV in heavier nuclei to a peak ($\approx$ 30 mb in carbon) at 800 MeV, after which it begins to fall. The corresponding thick-target yield per proton (in carbon) rises by a factor of five per 100 MeV from 300 to 600 MeV, by another factor of five from 600 to 900 MeV, where it has a value of 0.2 per proton, and rises very slowly above that energy. Total yield is not necessarily the most significant quantity to consider, but others, such as intensity in the forward direction, or total number above a fixed energy, would further accenuate the advantage of high proton energy. Moreover, the total yield of neutrons increases by only a factor of four from 400 to 1000 MeV, so that if one acknowledges neutrons as the most important source of background, the ratio of useful beam to background also increases rapidly with energy in this range. Thus we are led to the conclusion that a proton energy of about 800 MeV is much superior to a lower energy and that there is little to gain by going higher, unless other phenomena, such as K production, are to be included.

2. External Beam

The problems of radiation damage, activation, and shielding for high-intensity machines have long been recognized. On the basis of general experience with FM cyclotrons and of specific investigations carried out at the Berkeley 184-inch cyclotron by a group from Oak Ridge, and by the CERN SC division on their machine, it is generally agreed that a machine of that general size and character could tolerate about 10 μA of full-energy beam striking the internal structure. "Tolerate" means that current operational methods could be used

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without undue loss in time and efficiency, whereas more intense beams lost internally would necessitate elaborate servicing, resembling nuclear-reactor techniques. Since 10 μA is a minimum acceptable current for a new machine, most of the beam must be extracted and put on an external target, whether the experimental physicists like it or not. This is probably the most definite item on the list of requirements; efficient extraction of the primary beam is essential.

3. Duty Factor

On this subject, there is room for discussion. Counter experiments almost always call for a beam as uniform in time as possible, whereas bubble chambers require short pulses with not too high a repetition rate. It is unquestionably advantageous to have a machine that is capable of operating at a duty factor close to 100%, however, in many cases, a few per cent is acceptable and one can learn to live with much smaller values, as demonstrated at the Stanford electron accelerator. Whatever absolute importance this feature may have will probably be masked by personal tastes in accelerator type and experimental technique. It should be remembered that the resolution times available in detecting devices now overlap the rf periods of most accelerators, so that an rf structure in beam can determine the effective duty factor in certain classes of experiments; conversely, it may be possible to exploit a tight rf bunching for some purposes.

4. Variable Energy

For π- and μ-meson work, ability to vary the proton energy is not important. For proton and neutron experiments, such a feature would be convenient. This item is of the nature of a "fringe benefit"--it would find application if easily available, but would not have a serious influence on a choice of accelerator.

5. Capital Costs

In one sense, the capital cost of an accelerator itself has ceased to have the meaning it had 25 years ago, when it represented a special outlay, and the remaining effort was geared to a physics department's normal procedure. For the type of facility being discussed here, the cost of shielding, experimental areas, and equipment and staff to make the laboratory truly effective would be even greater in proportion to accelerator cost than in present installations. Having chosen a basic accelerator type, it is thus short-sighted to skimp on items which will contribute to simple and reliable operation. However, that is a matter of detailed design; what is more important here is that the scale of continuing costs is determined in considerable part by the cost of the basic components. Like automobiles, expensive accelerators are more expensive to run and to repair or modify. Preliminary cost estimates and layouts should be used, not so much to show that a particular accelerator is a bargain or a luxury, but as one indicator of the commitment which must be made for the next decade and longer.

B. SPECIFIC ACCELERATORS

I shall now describe various types of accelerators which might be used as meson factories. Since the spiral-ridge cyclotron is so strongly represented at the meeting,† and since several papers will be presented on high-energy designs, it will be treated only briefly here. Some of the general features to be discussed below are summarized in Table I.

1. Synchrocyclotron

Before proceeding with new possibilities, let us first review the present state and potentialities of the conventional FM cyclotron, which has dominated the π-meson field until now. Since it is intended that the new machines should surpass the synchrocyclotron is performance, their attractiveness must be measured by a comparison with facilities presently available or attainable by relatively minor modifications.

The best average currents attained thus far are around 1μA. Most machines have a poor duty factor, but in a few cases duty factors close to 100% have been achieved by means of auxiliary accelerating electrodes which control the beam at the outer radius. There is no reason, in principle, why the currents should not be increased substantially, though it must be admitted that new developments have been introduced very slowly. This has been the case for various practical reasons--lack of money and manpower, minimal shielding, and adamant users who prefer to go on with their work rather than shut down for some months under a promise of better performance. If some "meson-factory" projects get seriously under way, we should anticipate an increased effort to improve existing synchrocyclotrons.

Studies are under way, principally by the 184-inch cyclotron group at Berkeley, to see if it is feasible to stack preaccelerated beam at a high repetition rate, in the style of MURA's FFAG designs. There also seems to be a possibility of improving source efficiency by a source geometry and extraction method independent of the main rf system. The objection has been raised that extraction is more difficult than for a CW cyclotron, in which nonlinear resonances and controlled acceleration are available. However, beams do come out of synchrocyclotrons by themselves; Carnegie Tech has used such a beam for a long time, and a recent report from Japan[1] claims 50% efficiency with a little help from electrostatic deflection.

There is thus a fair chance that within the time required to build a new machine, we will see 700-MeV external beams of 10 μA at 100% duty factor, from synchrocyclotrons. In that case, a 400-MeV 100-μA installation would be outclassed in meson intensity, according to the discussion of machine energy in the first section. If these developments move faster than in the past, it might be attractive to consider a new, and well-modernized, synchrocyclotron, for there is the added advantage of high average field, implying a smaller magnet and fewer tons of shielding than for a CW cyclotron.

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†International Conference on Sector-Focussed Cyclotrons, University of California at Los Angeles, April 17-20, 1962.

Table I. Comparison of accelerator types

Type	Probable energy (MeV)	Current (μA)	Duty factor (%)	Extraction	Variable energy	Cost* ($M)
Synchro-cyclotron	600-800	1-10	100	Difficult	No	---
AGS	Unlimited	1-10	10-20	Easy	Yes	7-8 (670 MeV)
FFAG	Unlimited	100	?	Very difficult	No	10-12 (750 MeV)
CW cyclotron	400-800	100-1000	100	Difficult	No	5 (400 MeV) 10-12 (800 MeV)
Electron accelerators	300-1000	100-1000	1-25	Easy	Yes	---
Proton linear accelerator	600-1000	100-1000	1-10	Easy	Yes	15-17 (800 MeV)

*These are rough guesses intended to cover component costs, development, salaries, and accelerator building, but nothing else.

2. Alternating Gradient Synchrotron

This type of accelerator can by now be considered as well-known, though it has been seriously undertaken only for much higher energies. We include it here mainly because it offers the simplest means of going above 1 GeV in energy, though it has other attractive features as well. With a little optimism, one can claim competitive intensity; by injecting at 10 MeV into a 700-MeV ring for several turns, 10^{12} particles per pulse could be produced, which corresponds to 10 μA at a 60-cps repetition rate.

Fortunately for the purpose of this presentation, a preliminary study was made recently at Berkeley of a synchrotron intended primarily to produce intense beams of heavier ions at 200 MeV/ nucleon for use in bio-medical research. The same ring could be used to accelerate protons to 670 MeV. The parameters used for the study give an indication of how a small synchrotron might look; a few are given in Table II. *

Table II. Possible parameters for an alternating gradient synchrotron.

Machine radius	50 ft
Radius of curvature	12.5 ft
Peak field	11.3 kG
Number of magnets	40
Weight of steel	61 tons
Weight of copper	12 tons
Stored energy	197 kJ
Useful aperture	1.5 by 5 in.
Maximum energy gain per turn at 20 cycles	24 keV

The negligible amounts of steel and copper needed are noteworthy, as well as the large circumference factor, which leaves 6 ft of open space for every

*A recent report from Saclay concerning a proposed 60-GeV synchrotron includes a brief study of a 1.5-GeV, 50-cycle synchrotron for use as an injector.

2 ft-long magnet. Single-turn extraction would be accomplished by pulsed magnets, and, for longer times, by the Wright-Piccioni method used on the Cosmotron. The duty factor would not be very good because of the sine-wave excitation, but steady secondary beams could be produced for 10 to 20% of the time as the sine wave goes through its peak.

On the basis of the Berkeley study, it would appear that the cost of this machine to be entered in Table I is \$7-8 M.

3. FFAG

The fixed-field alternating-gradient principle had always been assumed to be best suited for much higher energies. However, in the course of preparing their new proposal, and stimulated by the growing interest in high-intensity machines below 1 GeV, the MURA group came to the realization that a small FFAG could compete in cost and performance with the other types of accelerators that have been suggested. The FFAG would have a unique advantage in that the protons could be held at full energy and used at a rate independent of the acceleration cycle--for example, they could be held until the rf structure had disappeared, before putting them on target.

Extraction presents a serious problem in this type of machine. Since extraction is also an important feature in the layer version, considerable effort is being devoted to the question at MURA, by means of both computations and experimental work on the spiral-sector and the 50-MeV electron models. Single-turn extraction has been accomplished with good efficiency, and computations indicate that resonant extraction can be stretched over ten turns at about 30% efficiency. There are suggestions for improving these figures, but it is not yet clear, even on paper, how far one might hope to go.

Table III. Possible parameters for an FFAG synchrotron.

	500 MeV	750 MeV
Maximum field (kG)	10	10
Circumference factor	2.2	2.2
Radius (m)	8.0	10.3
Injection energy (linac) (MeV)	20	20
Radial width (cm)	70	100
k	22.6	22.6
Spiral angle (deg)	81	81
Stability limit (cm)	4 by 4	5 by 5
Magnet weight (tons)	500	650
Magnet power (MW)	1.5	2.0

Table III gives two possible sets of parameters, for 500 and 750 MeV. The rf system would consist of two stages--to 100 MeV at 200 cps, and on from 100 MeV at 50 cps. If protons were injected at 20 mA for 25 turns, the resulting average current would be 100 μA. These injection figures correspond to 10% of the calculated space-charge limit and a filling of transverse phase space proportionally less than has been accomplished experimentally on the models.

As far as cost is concerned, an estimate has been made at MURA by scaling down various figures from the larger machines. The portion of the cost which belongs in Table I is $10-12 M for the 750-MeV case, and perhaps $8-10 M for the 500-MeV case.

4. Spiral-Ridge Cyclotron

As promised earlier, I shall restrict myself to a few general remarks here. The widespread appeal of this type of accelerator arises from the fact that the basic machine is well tested by time and is familiar in detail to the largest number of people. Experience with the added ridges and higher energies will accumulate rapidly in the smaller machines now being completed. Beam currents up in the milliampere range are common at low energies, and currents in a large machine would actually have to be held far below present levels. Thus it would seem that a bigger cyclotron is the easiest and surest solution to the meson-factor problem.

On the other hand, the change in scale is so great that the feeling of familiarity may be misleading. The present concept of an 800-MeV cyclotron calls for a pole diameter more than twice that of an FM cyclotron of the same energy, because the central field must be low to allow for flutter and isochronism. A conventional dee is not applicable, both for electrical and mechanical reasons, and a system of cavities or of several dees in the valley regions is necessary.

Considerable skepticism has been expressed concerning the possibility of efficient extraction. Extensive calculations have been made, at Oak Ridge and elsewhere, on resonant extraction schemes, and one might expect by now that the efficiency would surpass 50%. However, that is a long way from the 90% one would demand for a 100-μA external beam, and it is difficult to see how one could guarantee, or even expect, an efficiency that high on the basis of calculation alone. This point should be much clearer in the near future, thanks to electron model experiments at Oak Ridge and MURA, and to the fact that similar schemes will be tried on a number of the new spiral-ridge cyclotrons.

The cost quoted in Table I is based on two available estimates at 400 and 800 MeV. The dependence of cost on energy is certainly not linear; the result is rather due to poor statistics.

5. Hybrids

It becomes apparent after reflecting on synchrocyclotrons, isochronous cyclotrons, and FFAG's that there really is a continuum of possibilities obtained by combining the three concepts in varying degrees. The magnet problem in the spiral-ridged cyclotron may be eased considerably by abandoning isochronism and substituting a little frequency modulation at a high repetition rate. If we further ease the magnet problem by removing the central section and injecting at an intermediate energy, we approach the FFAG principle, which consists in greatly reducing the width of the outer annulus by increasing the gradient of the average field. Thus many variants are possible, including the choice of combining pure types either in the same magnet or in separated machines, regarding the inner one as an injector for the outer one. Up to now, there does not appear to be any striking advantage in mixing types, but as designs become more specific and optimum configurations become important, it might be useful to keep such variations in mind.

6. Electron Accelerators

High-energy electrons can also produce mesons in substantial numbers. The yield per accelerated particle is lower than for protons by a factor somewhat greater than 137, but the threshold is much lower, and large currents are easier to produce. According to a recent estimate,[2] analyzed π beams of 10^6/sec could be produced by 100 μA of 760-MeV electrons. This figure is well below the value of 10^9/sec expected from protons of comparable energy and current, but falls in the range of intensities now available.

The technology of linear accelerators has advanced so far since the Stanford machine was built that one can contemplate currents up to 1 mA at high energy with duty factors of a few percent, and there are competent commerical firms in this field to undertake development and construction work. The cost and complexity of such an accelerator would undoubtedly be much tooo great to compete with proton machines as a meson factory alone; it should rather be pointed out that it is technically feasible to improve enormously on present linear accelerators in intensity and duty factor, and that, along with its other applications, such a machine would yield very respectable fluxes of π mesons.

An interesting possibility involving electrons is the FFAG betatron. The use of a static guide field permits simultaneous acceleration of electrons of all energies, and a duty factor which depends only on the cycling of the accelerating flux. Duty factors of 25% and currents of greater than 100 μA should be attainable.

7. Proton Linear Accelerators

Finally, we come to the accelerator which has been considered most seriously as an alternative to the spiral-ridged cyclotron. The linear accelerator was the first machine to receive detailed attention as a meson factory when Harwell almost decided to build a 600-MeV version in the early fifties, but finally chose to undertake a 7-GeV proton synchrotron instead.

The most attractive feature of a linear accelerator is the fact that there is no extraction problem at all. The beam would emerge from the end with a quality and energy spread which could be safely predicted in advance. The newest ion sources make it possible to produce average currents in the milliampere range, and it is more likely than for a cyclotron that the full current could be used, since the source of activity and radiation would be localized some distance from the accelerator itself. The obvious drawback to the linear accelerator is its duty factor; while it can, in principle, be run continuously, the rf power requirements are so great that a value of 5% or so represents a practical upper limit in duty factor.

By happy coincidence, a sizeable effort is being applied these days to the study of a synchrotron for 300 GeV or more. Such a machine would require an injection energy of several GeV, an application for which a linear accelerator would have a number of advantages. Thus we find that the design of high-energy linear accelerators is being actively pursued not only at Yale University, but also at Berkeley and Brookhaven; in addition, MURA has already designed a 200-MeV machine for injection into an FFAG, and Harwell has renewed its interest in linear machines.

There are two factors which make an extension of the linear accelerator nontrivial: one, a matter of principle, and the other, a practical one. The first arises from the fact that the protons would be passing through an energy range which is neither nonrelativistic or extreme-relativistic. The velocity spread in the beam is sufficiently great that phase focusing is essential to keep the protons bunched, but sufficiently small that the effect of a mismatch would not be detectable until much farther along the machine. Electron accelerators are much simpler in this respect, since the velocity is highly homogeneous and entire sections of accelerators may be out of operation without more effect than a proportional lowering of the final energy. The practical point mentioned above is that a drift-tube-loaded accelerator exhibits increasing rf losses per unit length with increasing particle velocity, so that a changeover is required to a disk-loaded structure at some energy. Since the latter is characterized by losses which increase with decreasing particle velocity, an optimization procedure must be found to determine the proper energy for changeover, and the proper frequencies for the two portions of accelerator.

The parameters currently in favor for a linear accelerator are approximately as follows: The drift-tube-loaded portion would consist of six to ten 200-Mc tanks taking the beam to 200 MeV in a length of about 150 m. The disk-loaded portion would consist of some fifty 1200-Mc wave-guide sections accelerating the beam from 200 to 800 MeV in 600 m. The peak rf losses for each portion would be about 10 and 50 MW, respectively. If we assume a duty cycle of 5%, and an average current of 1 mA, the cost would be about $5 M for the 200-Mc portion and $10-12 M for the 1200-Mc portion, or a total of $15-17 M for the items to be included in Table I.

The recent advances in cryogenic techniques with respect to cost and reliability have led to a growth of interest in the practicality of superconducting rf cavities for general applications and, in particular, for linear accelerators. To my knowledge, the greatest effort in this direction is at Harwell[3] by the PLA group, which built the first 50 MeV of the once-proposed 600-MeV accelerator. Some work is also in progress at Zürich in connection with their plans for a meson factory, and at Stanford, for possible application to electron accelerators.

As normal materials, such as copper, are cooled down, the surface resistivity decreases in accordance with classical theory until the skin depth is comparable to the collision mean free path of electrons in the atomic lattice. At lower temperatures the surface resistivity becomes constant, and only a factor of ten below the room temperature value for copper at a few hundred megacycles. Superconducting materials also exhibit a skin effect that is dependent on temperature and frequency even though the dc bulk resistivity is zero. On the basis of existing measurements with specially prepared superconducting surfaces and at negligible power levels, one is led to expect reduction in rf losses by factors of more than 10^4 at a few hundred megacycles. The most relevant experimental result known to me was obtained at Stanford--a Q-measurement of 35×10^6 on a tin cavity at 3000 Mc at a power level corresponding to a magnetic field strength of 30 G at the wall. The Q value is a thousand times better than for copper at room temperature, and was obtained without any special treatment of the surfaces.

A superconducting accelerator would probably be operated continuously, for the buildup times are measured in seconds and starting one up would be a problem in itself. The skin losses in a 600-MeV 200-Mc machine would be about 2 kW, compared to 600 kW beam power at 1 mA. Such a device would not be cheap, but the economic burden would be shifted to the refrigeration plant and accelerator structure. An estimate from Harwell on component costs for a 600-MeV 1-mA machine leads to a total of $15 M

C. CONCLUSION

I doubt that the long, if not impressive, list of accelerator types presented here will seriously affect the plans of any of the immediately interested parties. The various advantages and disadvantages are difficult to compare in any absolute sense, and the differences in quoted costs are not great, in view of the uncertainty of the figures* and the many additional capital and continuing expenses that are omitted. Since most groups interested in meson factories would be undertaking an accelerator facility far larger than their institutions have previously assimilated, familiarity and past experience will be particularly important for efficient and rapid completion. For example, Oak Ridge or UCLA would probably do best with a cyclotron, and Yale with a linear accelerator, whatever the prevailing "expert" opinion might be as to the relative merits of the two types.

Since the investment in money and manpower will be large, and since the interesting problems in this energy range are fairly well-defined, I believe that the supporting agency would be justified in asking for a proposed research program, with experiments laid out in sufficient detail to demonstrate the applicability of the particular accelerator. Any significant differences between accelerator types would be most likely to appear in such an analysis.

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*It is, however, fairly certain that the linear accelerator will continue to run ahead of the others.

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